Ministry of Natural Resources

23

CLIMATE
CHANGE
RESEARCH
REPORT
CCRR-23

Responding to Climate Change Through Partnership

Implications of a Potential Range Expansion of Invasive Earthworms in Ontario's Forested Ecosystems:

A Preliminary Vulnerability Analysis

Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change
MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change
MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt
MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

Implications of a Potential Range Expansion of Invasive Earthworms in Ontario's Forested Ecosystems:

A Preliminary Vulnerability Analysis

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Abstract

The earthworm is a well known ecological engineer, famous for its ability to ingest and integrate soils through different layers, for its contribution to agricultural productivity, for its role as food for wildlife, and for its use by anglers as fish bait. Although no native earthworm species exist in Ontario (native North American earthworm populations are thought to have been extirpated by the Wisconsinan glaciers and re-colonization by southern populations has not occurred), many earthworm species have been accidentally or intentionally introduced. At present, 17 non-native European and two North American (non-native to Ontario) earthworm species survive in the province. Since their arrival, earthworms have been used to enhance soil productivity in agro-ecosystems and urban areas. Conversely, most forested ecosystems in Ontario have evolved without earthworms and their introduction and establishment could significantly alter forest soil structure, chemistry, and biodiversity, including understory vegetation, soil fauna, and belowground fungal communities.

In a warming climate, the potential for some earthworm species to expand their range into forested ecosystems or expand populations already established in forested ecosystems will increase. Although little is known about the real and potential threat of invasive earthworms to Ontario's forested ecosystems, studies in the Minnesota hardwood forest, Quebec old growth forest, and Alberta boreal forest suggest that Ontario's forests could be susceptible, with the potential for significant ecological change and socio-economic impacts.

In this study, we undertook to review knowledge of the status and distribution of earthworms in Ontario, explore the use of selected ecological and socio-economic variables to complete a preliminary vulnerability analysis of forested ecosystems to earthworm invasions in a warming climate, comment on the known and potential ecological effects of earthworms on Ontario's forests, and recommend next steps for future research and management actions.

The potential invasiveness of each species was ranked and scored using five criteria: distribution and abundance, transportability as bait, reproduction, relationship to the minimum January isotherm, and pH tolerance. Three epigeic species (*Aporrectodea rosea, Dendrobaena octaedra, and Dendrodrilus rubidus*), three endogeic species (*A. trapezoides, A. tuberculata, and A. turgida*), one epi-endogeic species (*Lumbricus rubellus*), and one anecic species (*L. terrestris*) ranked high as potential invasive species that may require attention as Ontario's climate warms.

Résumé

Répercussions d'une propagation possible de vers de terre envahissants dans les écosystèmes forestiers de l'Ontario : une analyse de vulnérabilité préliminaire

Le ver de terre est un « ingénieur écologique » bien connu pour ses rôles divers : il ingère des particules de sol et favorise l'intégration de couches de sol; il favorise la productivité agricole; il est source de nourriture pour la faune; il est utilisé comme appât par les pêcheurs. Bien que l'Ontario n'en ait pas d'espèces indigènes (les populations indigènes de l'Amérique du Nord auraient été détruites par la glaciation du Wisconsinien, et une recolonisation par des populations méridionales n'a pas eu lieu), de nombreuses espèces de vers de terre présentes aujourd'hui en Ontario y ont été introduites accidentellement ou intentionnellement. Aujourd'hui, 17 espèces européennes et deux espèces nord-américaines (mais non de l'Ontario) survivent en Ontario. Depuis leur arrivée chez nous, les vers de terre sont utilisés pour accroître la productivité des sols dans des écosystèmes agricoles et des zones urbaines. La plupart des écosystèmes forestiers en Ontario ayant évolué sans vers de terre, l'introduction et l'établissement de ceux-ci dans ces écosystèmes pourraient modifier de façon importante la structure, la composition chimique et la biodiversité du sol, dont la végétation de sous-étage, la faune du sol et les communautés de champignons souterraines.

Dans le contexte du réchauffement climatique s'accroîtra la possibilité que certaines espèces de vers de terre puissent étendre leur territoire et gagner des écosystèmes forestiers, ou puissent élargir leurs populations dans les écosystèmes forestiers où elles sont déjà établies. Bien qu'on sache peu de choses sur les dangers réels ou potentiels que causerait une invasion de vers de terres dans les écosystèmes forestiers de l'Ontario, les études réalisées dans des forêts de feuillus du Minnesota, des forêts anciennes du Québec et des forêts boréales de l'Alberta laissent entendre que les forêts ontariennes risqueraient de subir d'importants changements écologiques et que ceux-ci pourraient avoir d'importants effets socioéconomiques.

Dans cette étude, nous examinons les données sur l'état et la répartition des populations de vers de terre en Ontario, utilisons un choix de variables écologiques et socioéconomiques pour réaliser une analyse préliminaire de la vulnérabilité des écosystèmes forestiers à une invasion de vers de terre dans le contexte d'un climat qui se réchauffe, faisons des observations sur les effets écologiques connus et potentiels des vers de terre sur les forêts ontariennes et recommandons les prochaines étapes à prendre en fait de travaux de recherche et de mesures de gestion.

Le risque d'invasion de chaque espèce est hiérarchisé au moyen de cinq critères : répartition et abondance; déplacement des vers utilisés comme appât; taux de reproduction; relation avec l'isotherme minimale de janvier; tolérance au pH du sol. Trois espèces épigées (*Aporrectodea rosea, Dendrobaena octaedra* et *Dendrodrilus rubidus*), trois espèces endogées (*A. trapezoides, A. tuberculata* et *A. turgida*), une espèce épiendogée (*Lumbricus rubellus*) et une espèce anécique (*L. terrestris*) sont placées haut au classement des espèces potentiellement envahissantes qui pourraient nécessiter qu'on y prête attention à mesure que le climat de l'Ontario se réchauffera.

Acknowledgements

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Foreword

In a rapidly changing climate, decision-makers require some sense of the vulnerability of ecological and social systems to create visionary goals and objectives for the future and propose actions to reduce or eliminate that vulnerability. In this context, vulnerability is the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climatic change. In a world where climate change and other stressors are affecting natural and social systems, resource managers are working to integrate climate models (top-down projections of possible future climates) with vulnerability analyses (bottom-up assessments of how species and systems might be affected) to inform decision-making.

Climate models are projections rather than predictions: they are based on assumptions that may be incorrect, the response of Earth's climate to future greenhouse gas emissions is uncertain, and changes in human behaviour and the corresponding rate and volume of greenhouse gas emissions are unknown. Vulnerability analysis uses a suite of ecological and social indicators to provide information about how a system is responding to change. Some indicators, such as an animal's thermoregulatory tolerance, are species specific while others, such as water temperature, provide information about the changing dynamics of entire systems. With this knowledge, management actions can be used to reduce or eliminate the vulnerability or support adaptation. Since future change is certain, effective monitoring is also a critical aspect of adaptation, and raises the question: "Will existing monitoring inform effective decision-making in a rapidly changing climate?" Accordingly, existing monitoring programs require re-examination to ensure they include the climate sensitive indicators required to complete vulnerability analyses for ecosystems and are implemented at a frequency and/or scale relevant to expected changes in climate.

Given the uncertainty associated with the use of climate models and known and potential gaps in monitoring programs, vulnerability assessments are based on a variety of qualitative (e.g., expert opinion solicited during workshops) and quantitative (e.g., measures of species phenotypic and genetic plasticity) indices. The intent is to use these indicators to support practitioner's planning needs. As with any adaptive management process, ongoing assessment and modification are required as new information emerges.

At this early stage in the evolution of vulnerability assessment techniques, it is important that practitioners learn by doing and pass on new knowledge about what works and what does not. Accordingly, this and other vulnerability assessments have been prepared using the best available information under the circumstances (e.g., time, financial support, and data availability) and are included in this research series to support MNR and other organizations engaged in adaptive management. These assessments are intended to collectively inform decision-making, enhance scientific understanding of how natural assets respond to climate change, serve as case studies to help practitioners design their own vulnerability assessments, and help resource management organizations establish research needs and priorities.

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Contents

1.0 Introduction

The frequency, intensity, and geographic extent of natural disturbances (e.g., wildfire, insects, and diseases), extreme events (e.g., ice storms, drought, and flooding), and biological invasions in forested ecosystems are influenced by climate change (Stocks et al. 1998, Ayres and Lombardero 2000, Flannigan et al. 2000, Bohlen et al. 2004a, Tiunov et al. 2006, Candau and Fleming 2008, Colombo 2008, Addison 2009, Stocks and Ward 2011). These forces and factors can singly or cumulatively alter ecosystem composition, structure, and function by affecting the availability of key resources (e.g., elements such as carbon and phosphorus that are important for bio-geochemical cycles) or by introducing new species that change species-to-species and species-to-habitat relationships (Bohlen et al. 2004a, Frelich et al. 2006, Addison 2009). The earthworm is an ecological engineer (Jones et al. 1994, Hale 2004, Frelich et al. 2006) and if some of the earthworm species now abundant in southern and central Ontario and/or species found in pockets of habitat in northern Ontario are able to expand their range and/or increase their population size in response to climate change, forested ecosystems may be adversely affected.

No native earthworms exist in Ontario. Populations native to northern North America are thought to have been extirpated by the Wisconsinan glaciers and re-colonization by southern populations has not occurred (Tiunov et al. 2006). However, many species have been introduced to Ontario. Currently, 17 non-native European and two North American (non-native to Ontario) earthworm species survive in the province. Many of these species were accidentally or intentionally introduced by settlers. Since their arrival, earthworms have thrived in agro-ecosystems and urban areas, and have been referred to as an indicator of high soil fertility because they enhance nutrient cycling, improve soil structure and texture, and increase aeration and water filtration in support of crops and garden plants (Lee 1985, Edwards and Bohlen 1996: 162, 202). Conversely, most forested ecosystems in Ontario have evolved without earthworms and their introduction and establishment could significantly alter forest soil structure, chemistry, and biodiversity, including understory vegetation, soil fauna, and belowground fungal communities (Bohlen 2004a,b; Frelich et al. 2006). In addition, it is possible that expanding earthworm populations will increase emissions of nitrous oxide (N_2O), a powerful greenhouse gas (Evers 2009).

In a warming climate the potential for some earthworm species to expand their distribution into forested ecosystems, or add to already established populations, will increase. Although little is known about the real and potential threat of invasive earthworms to Ontario's forested ecosystems, studies in the Minnesota hardwood forest (Hale 2004, Hale et al. 2005a,b; Holdsworth et al. 2007), Quebec old growth forest (Wironen and Moore 2006), and Alberta boreal forest (Cameron et al. 2008) suggest that Ontario's forests could be susceptible, with the potential for significant ecological change and socio-economic impacts.

In this report, we describe the 19 earthworm species found in Ontario, assess their mobility and survival potential in more northerly ecosystems in a warming climate, comment on their potential effects on Ontario's forests, and recommend research needs in support of applying an adaptive approach to their management.

2.0 Goals and Objectives

The goal of this work was to assess our knowledge of current and potential effects of invasive earthworms on the forested ecosystems of Ontario in a warming climate. The objectives were to:

1. Review knowledge of the status and distribution of the 17 non-native European and two North American (non-native to Ontario) earthworm species in Ontario.
2. Explore the use of selected ecological and socio-economic variables in a preliminary vulnerability analysis to assess the potential for earthworms to further invade forested ecosystems in a warming climate.
3. Comment on the known and potential ecological effects (e.g., on forest soils, understory vegetation, trees, microbial populations, and mycorrhizae) of earthworms to Ontario's forests.
4. Recommend next steps for research and management.

We present this information in the larger context of climate change and adaptive management.

3.0 Methods

To determine their invasive potential and ecological effects, we reviewed the literature on the ecology of the 19 earthworm species found in Ontario and selected five indicators of mobility and survivability to include in an 'invasion index'. We used this index to assess the potential for northward range and/or population expansion. For the 'invasion index' we selected five variables for which data and information were readily available: current distribution and abundance (i.e., commonness and geographical extent of distribution in Ontario), transportability (i.e., as bait), reproduction strategies (i.e., asexual and/or sexual), the isotherm of the most northerly record of distribution (as a proxy for survival in cold climates), and soil pH preference (as a measure of tolerance to acidic soils). Each variable in the index was evaluated for each species and scored based on a scale of high (5), medium (3), and low (1) (Table 1). Individual variable scores were summed to estimate the overall 'invasion potential' for each species. We then classified the overall 'invasion potential' as high (20-25), medium (11-19), and low (≤10).

To estimate climate warming for the area of interest, we used Version 3 of the Canadian Global Climate Model (CGM3) with the A2 scenario provided by Natural Resources Canada (http://cfs.nrcan.gc.ca/subsite/glfc-climate) to generate potential isothermal boundaries of the minimum January temperature for four time periods: 1971-2000, 2011-2040, 2041-2070, and 2071-2100.

Table 1. *Ranking system developed as a preliminary invasion index for earthworms in Ontario.*

Ranking of Invasion Potential	Invasion Variables				
	Abundance and distribution	Reproduction	Transportability as bait	Most northerly isotherm	pH tolerance
Low (1)	Scarce and limited distribution	————	No has not been documented as bait	Warmer than -10°C	Prefers alkaline soils
Medium (3)	Scarce but somewhat widespread Somewhat abundant in pockets Abundant and widespread in southern Ontario	amphimictic	Has been documented as occasionally occurring (accidental) in bait Potentially collected by individuals for bait	-15°C to -10°C	Can survive in acidic soils (3.5-7.4)
High (5)	Abundant and widespread in southern Ontario and pockets in northern Ontario	Parthenogenic	Yes, commonly used as bait	-20°C to -15°C or colder	Ubiquitous (3.5-7.4)

[1]For the purposes of this paper, two generic categories of reproduction were selected: sexual reproduction (amphimictic) involving two worms and asexual reproduction (parthenogenic) involving one worm. Amphimictic species were assigned to the 'Medium' category and parthenogenic species to the 'High' category.

4.0 The Role of Vulnerability Assessment in Adaptive Management

It is possible that the current changes – warming and increased variability – in Earth's climate will continue for decades, perhaps centuries, and will affect the way societies and their organizations engage in sustainable management of natural assets in Ontario's ecosystems. In response to climate change, jurisdictions will need to *learn while doing* (Lee 1999) to help adapt management decisions as ecosystems change.

Good planning and management translates ecologically meaningful and socially acceptable values and knowledge into action to access natural assets and to minimize the risk of adverse effects of their use (Manning

1994). It is anticipated that effective natural asset planning and management will aim to maintain ecological sustainability, will need to be socially acceptable, and will incorporate the known and potential vulnerability of ecological assets to climate change.

While agreement is widespread on the need to recognize and prepare for climate change in sustainable ecosystem planning and management, and to develop and integrate risk management strategies into current and new programs, adaptive processes are only now being described and operationalized (see Gleeson et al. 2011). The following exemplifies a process for assessing the vulnerability of natural and human assets to climate change and integrating these concerns into an adaptive approach to management:

1. Assess organizational readiness and where necessary improve the capacity to respond.
2. Establish or reconfigure a baseline against which to measure change and adaptation success.
3. Develop and use climate scenarios and socio-economic scenarios to help envision future conditions.
4. Complete vulnerability analyses based on the developed scenarios.
5. With the results of the vulnerability analyses, identify and develop adaptation strategies.
6. Implement the adaptation strategies.
7. Monitor the strategies to evaluate success and the need for adjustment.
8. Adjust management decisions where needed (Figure 1).

Here we explore the use of climate change modelling tools and techniques to complete steps 2 to 4 of an adaptive management process. For readers interested in exploring all the steps, Gleeson et al. (2011) provide a case study of the Lake Simcoe vulnerability assessment and adaptation strategy.

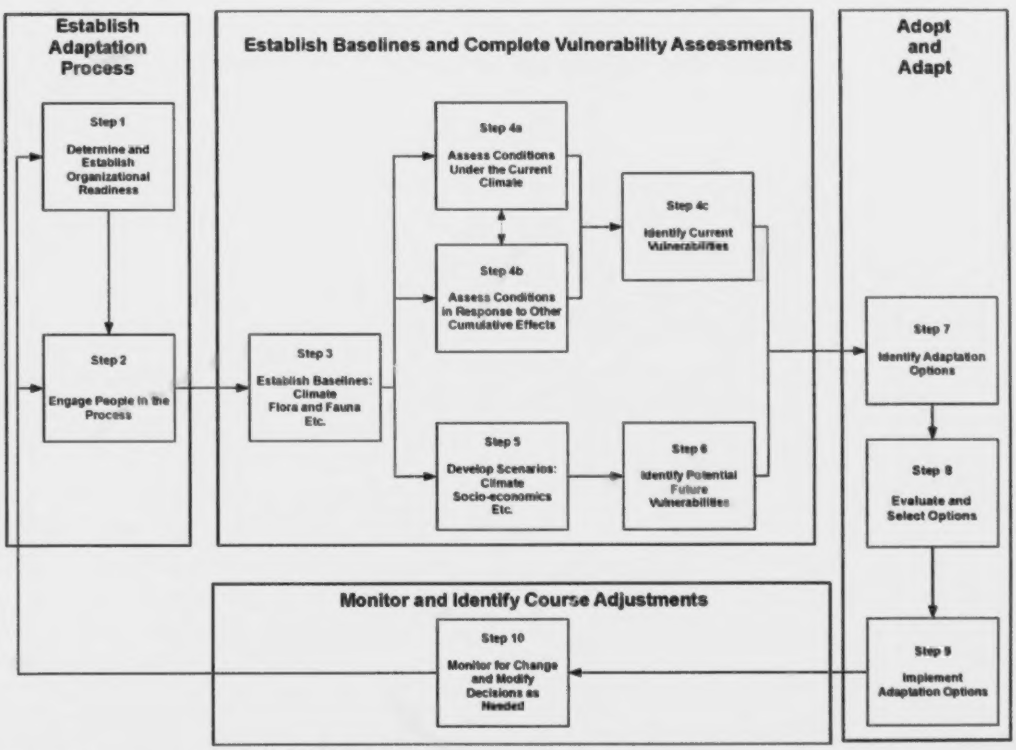

Figure 1. *A conceptual framework outlining the overall process involved in vulnerability assessments including establishing a process and baselines, completing vulnerability analyses, and developing, implementing, monitoring, and adjusting adaptation options as required (Source: Gray et al. 2011).*

5.0 Climate Change in Ontario

The average annual global temperature warmed by about 0.76±0.19°C over the last century (IPCC 2007), but warming in Canada was double the world average. The average temperature in Canada has increased about 1.2°C in the last 58 years (Environment Canada 2006). However, warming was not uniform across the country. For example, average annual temperatures increased about 2°C in northwestern British Columbia and the Kluane region of the Yukon Territory and by 1.2°C in south-central Canada, but did not change in Atlantic Canada (Environment Canada 2006). During this period, temperatures across Ontario increased 0 to 1.4°C (Chiotti and Lavender 2008).

In Ontario, temperature increases were significant in several locations during the 20th century. For example, the average annual temperature near Belleville on the north shore of Lake Ontario has increased by 1.14°C since 1921. In northwestern Ontario, east of Sioux Lookout, the average annual temperature has increased by 1.19°C since 1930. Significant warming in northeastern Ontario has also occurred. Since 1938, the average annual temperature north of Sudbury has increased by 1.14°C, and along the James Bay coastline, the average annual temperature has increased 1.24°C since 1895 (Lemieux et al. 2007). Warming has been more significant in winter and spring and is believed to have contributed to changes in evaporation rates, less snowfall, more rainfall, and shorter periods with ice cover (Mekis and Hogg 1999, Mortsch et al. 2000, Lemieux et al. 2005).

Modelled projections suggest that average annual air temperature could increase significantly by 2100. For example, regional projections generated using Version 2 of the Canadian Global Climate Model (CGCM2) and the A2 scenario suggest that Ontarians could experience significant warming, with maximum increases of annual average temperature of 6 to 7°C near Hudson Bay. The same model projects the average annual temperature of southwestern Ontario, including Toronto and the Niagara Peninsula, to increase by 5 to 6°C. Across the province, warming is expected to be greater in winter than in summer and greater in the north than in the south (Colombo et al. 2007:1).

As the Earth's atmospheric temperature warms in response to continued and increasing emissions of greenhouse gases, concurrent changes occur in soil temperature, soil moisture, and plant community structure, all of which can significantly affect the distribution and abundance of earthworm populations in existing and potentially new habitats. At the same time, invading earthworms may change ecosystem composition, structure, and function.

6.0 Earthworm Species Found in Ontario

The earthworm is known for its ability to ingest and integrate soils through different layers, for its contribution to agricultural productivity, for its role as food for the American Robin (*Turdus migratorius*) and other animals (e.g., Eastern Garter Snake, *Thamnophis sirtalis sirtalis*), and for its use by anglers as fish bait. There are three forms of burrowing behaviour used to classify earthworms into ecological groups: (1) horizontal burrowing by epigeic species that live in the upper soil horizons and consume leaf litter with high organic residue content but do not incorporate it deeper into the soil profile, (2) horizontal burrowing by endogeic species that forage just below the soil surface and consume smaller fragments and incorporate organic matter into the surficial layers of mineral soil, and (3) vertical burrowing by anecic species that create long term access to the soil surface and feed on partially decomposed organic matter by stripping apart litter fragments, which they incorporate deeper into the soil profile (Rizhiya et al. 2007). Although two species of earthworms tolerate freezing temperatures and are referred to as freeze tolerant, the rest are freeze intolerant; all species use a combination of physiological and behavioural strategies to survive the cold months (Reynolds 1977a, Holmstrup 2002).

Reynolds (1977a) published the most comprehensive natural history of earthworms in Ontario and included a distribution map for each species (Figures 2-16). Since that time, a few site-specific updates on the distribution of worms at specific locations have been published by Reynolds and Reynolds (1992), Reynolds and Mayville (1994), Tomlin and Fox (2003), and Addison (2009) (Table 2).

***Table 2.** Description and distribution of the 19 species of earthworms found in Ontario.*

Species	Ecological Classification[1]	Size[1]		Colour[1]	Habitat[1]	Distribution	
		Length (cm)	Diameter (mm)			Ontario[1,2,3,4,5,6]	Most northerly record in Canada
Allolobophora chlorotica (Green worm)	Endogeic	3-7	3-5	Normally green but can be yellow, pink, or gray	Wet areas, pastures, gardens, fields, forests, lake shores, estuary flats, and manure	Along Lake Erie and Lake Ontario and extending up to Lake St. Clair and the southern tip of Lake Huron (Fig. 2)	49-50°N (Manitoba)[5]
Aporrectodea icterica (Mottled worm)	Endogeic	5.5-13.5	3-5	Not pigmented	Garden soils, meadows and orchards	Only reported at The University of Guelph Arboretum in Guelph, Ontario (Fig. 3)	43°N (Guelph)[1]
Aporrectodea longa (Black head worm)	Epi-endogeic	9-15	6-9	Gray or brown	Cultivated areas, gardens, pastures, woodlands, along lakes and rivers	Greater Toronto Area, Ontario (Fig. 4)	>49°N (Alberta and Saskatchewan)[7] 49°N (Quebec)[8]
Aporrectodea rosea (Pink soil worm)	Endogeic	2.5-8.5	3-5	Usually un-pigmented but can have rosy or greyish areas	Fields, gardens, pastures and forests under stones and leaf litter, as well as on river and lake banks	Widespread across southern Ontario Timmins[6] (Fig. 5)	55°N (Manitoba)[9] 52°N (Alberta)[10]
Aporrectodea trapezoides (Southern worm)	Endogeic	8-14	3-7	Brown, brownish-red or red	Associated with the roots of plants, in gardens, cultivated areas, forests and along stream banks	Widespread across southern Ontario (Fig. 6)	55°N (Manitoba)[11]
Aporrectodea tuberculata (Canadian worm)	Endogeic	9-15	4-8	Unpigmented, but can be gray or white	Areas with high organic matter content or along stream banks, in ditches, compost, under logs and sometimes in manure	Widespread across southern Ontario Timmins[6] Rainy River area in northwestern Ontario (Fig. 7)	64°N (Nunavut)[11]
Aporrectodea turgida *(Pasture worm)*	Endogeic	6.0-8.5	3.5-5.0	Unpigmented	Gardens, fields, turf, leaf litter in forests, compost, banks of spring sand streams, wasteland, city dumps, and streams, and irrigated areas.	Widely distributed across southern and central Ontario Timmins[6] Rainy River area in northwestern Ontario (Fig. 8)	49-50°N (Manitoba)[9] 54.5-58°N (Alberta)[12]
Bimastos parvus (American bark worm)	Epigeic	1.7-6.5	1.5-3.0	Red	Associated with areas with high organic matter, and decaying logs	Canadian Agricultural Arboretum in Ottawa (Fig. 9)	60-61°N (Yukon)[13,14]
Dendrobaena octaedra (Octagonal-tail worm)	Epigeic	1.7-6.0	3-5	Red, dark red or purple	Along stream banks, under logs and leafy debris or in cool, moist ravines or seepage areas	Ottawa Valley to Lake Nipissing 120 km northeast of Thunder Bay Rainy River area in northwestern Ontario (Fig. 10)	55°N (Manitoba)[9] 54.5-58°N (Alberta)[12] 61°N (Yukon)[13]
Dendrodrilus rubidus (European bark worm)	Epi-endogeic	2-9	2-5	Red	Gardens, cultivated fields, stream banks, peat, compost and manure	Sporadically within southern Ontario, but have also been found along the northern portion of Lake Superior Timmins[6] Rainy River area in northwestern Ontario (Fig. 11)	55°N (Manitoba)[9] 53°N (Saskatchewan)[15] 54.5-58°N (Alberta)[12]

Eisenia foetida (Manure worm, Tiger worm or Red wiggler)	Epigeic	3.5-13	3-5	Normally reddish-brown or alternate red and brown segments	Manure or organic matter, dumps, forests and gardens	Haliburton County, far eastern and western parts of southern Ontario (Fig. 12)	49-50°N (Manitoba)[9] 53°N (Saskatchewan)[15] >49°N (Alberta)[7]
Eiseniella tetraedra (Square-tail worm)	Epigeic	3-6	2-4	Dark brown, green, or golden yellow	Lakes, streams and ponds	Associated with the Great Lakes but are more widely distributed in south western Ontario Rainy River area in northwestern Ontario (Fig. 13)	64°N (Nunavut)[11]
Lumbricus castaneus (Chestnut worm)	Anecic	3-5	3-5	Dark red, chestnut, violet and brown and very iridescent	Gardens, cultivated fields, pastures, forests, taiga, among organic matter such as compost, manure and leaf litter and in banks by water	Haliburton, Middlesex, Niagara and York counties (Fig. 14)	49°N (Quebec)[8]
Lumbricus festivus (Quebec worm)	Anecic	4.8-10.5	4-5	Ruddy brown and iridescent on the dorsal side	Pastures and river banks and in soil beneath leaf litter stones and manure	Found in a few areas along Lake Ontario, eastern Ontario and as far north as Lake Nipissing (Fig. 15)	49°N (Quebec)[16]
Lumbricus rubellus (Red marsh worm)	Epigeic	5-15	4-6	Brown or red-violet iridescent on the dorsal side and pale yellow on the ventral side	Places rich with organic matter, such as stream banks, under logs, parks, pastures, gardens and woody peat	Widely spread across southern Ontario and 120 km north of Thunder Bay Timmins[6] Rainy River area in northwestern Ontario (Fig. 16)	49-50°N (Manitoba)[9] 54.5-58°N (Alberta)[12] 60-61°N (Yukon)[13]
Lumbricus terrestris (Night crawler or Dew worm)	Anecic	30	10	Heavily pigmented, usually brownish-red or violet on dorsal side and yellowish-orange on ventral side	Gardens, lawns, pastureland, under logs, forests, riverbanks, streams, mud flats, woody peat, under cowpats, and in compost	Widespread across southern Ontario Moose Factory[4] Timmins Rainy River area in northwestern Ontario (Fig. 17)	55°N (Manitoba)[9] 54.5-58°N (Alberta)[12] 60-61°N (Yukon)[13]
Octolasion cyaneum (Woodland blue worm)	Endogeic	6.5-18	7-8	Blue-gray or white	Under stones and logs near stream banks, in water, in moss, ploughed fields, wet sand and forest soil	Haliburton and Perth counties Rainy River area in northwestern Ontario (Fig. 18)	49°N (Rainy River) >49°N (Alberta and Saskatchewan)[7]
Octolasion tyrtaeum (Woodland white worm)	Endogeic	2.5-13	3-6	Blue, milky white, gray or pink	Under logs, stones, peat, leaf litter, forests, stream banks, gardens, cultivated fields and pastures	Kawartha Lakes region southwestern Ontario along the Niagara Escarpment Timmins[6] (Fig. 19)	55°N (Manitoba)[9]
Sparganophilus eiseni (American mud worm)	Endogeic	15-20	2.5	Unpigmented or light pink and occasionally has a green/blue iridescence	Muddy banks of streams, lakes, rivers and ponds	Along the north shore of Lake Erie and the north eastern shore of Lake Huron (Fig. 20)	46°N (Quebec)[8] 46°N (Ontario)[1]

[1]Reynolds (1977a), [2]Lee (1985), [3]Addison (2009), [4]Tomlin and Fox (2003), [5]Reynolds and Mayville (1994), [6]P.A. Gray and R. Lalonde (personal observation), [7]Lee et al. (1998), [8]Reynolds (2010), [9]Reynolds (2000), [10]Reynolds and Clapperton (1996), [11]Reynolds (2004), [12]Cameron et al. (2007), [13]Teale (2007), [14]Berman and Marusik (1994), [15]Reynolds and Khan (1999), and [16]Reynolds (1977b).

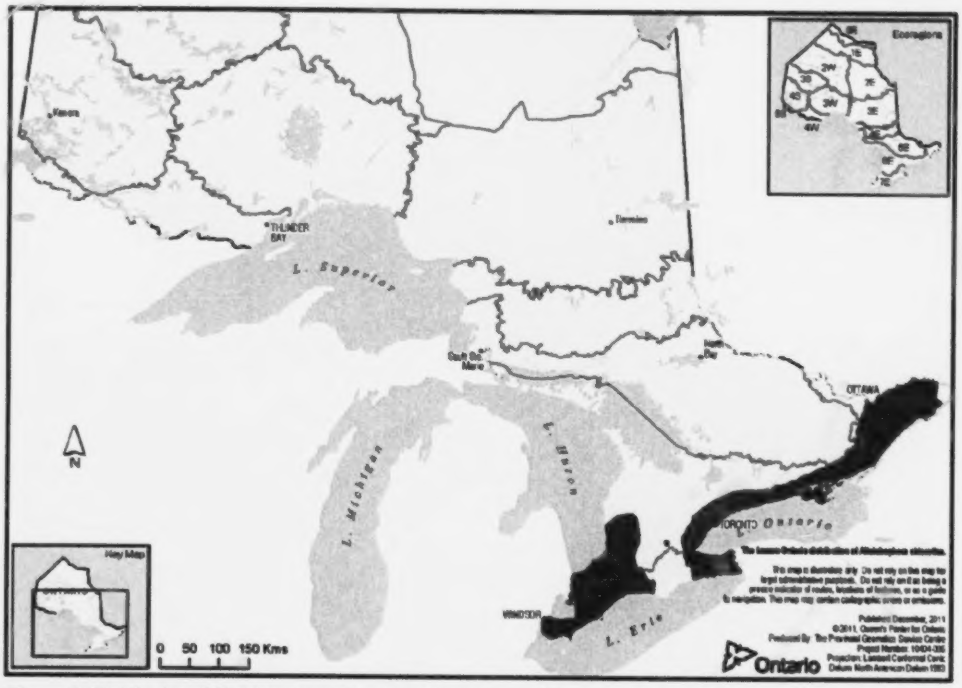

Figure 2: Distribution of Allolobophora chlorotica *(Green worm) in Ontario (adapted from Reynolds 1977a).*

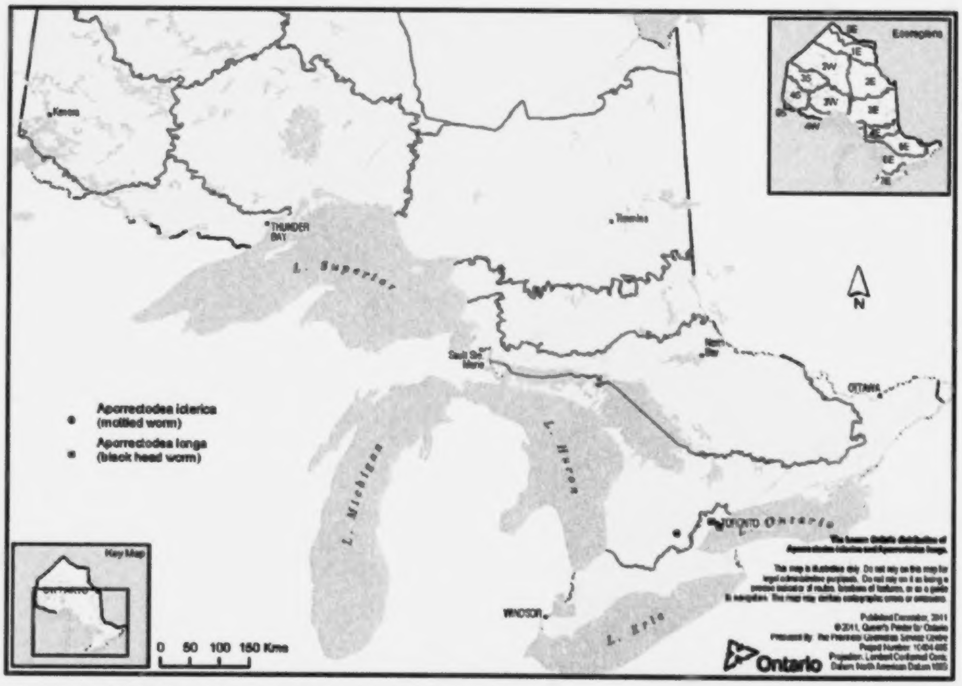

Figure 3: Distribution of Aporrectodea icterica *(Mottled worm) and* Aporrectodea longa *(Black head worm) in Ontario (adapted from Reynolds 1977a).*

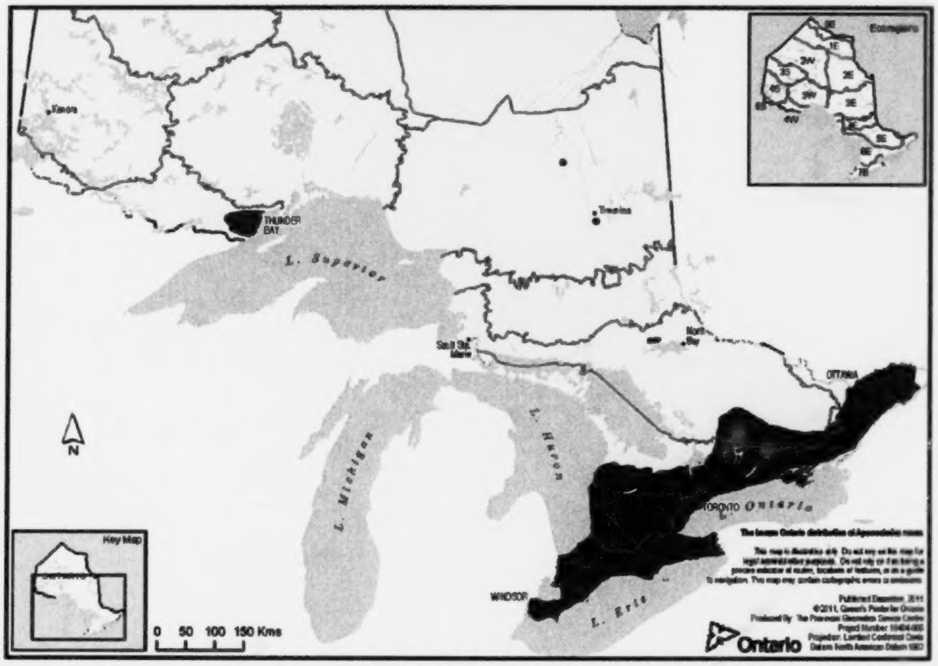

***Figure 4:** Distribution of* Aporrectodea rosea *(Pink soil worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994 with additional records by P.A. Gray and R. Lalonde, personal observation July*

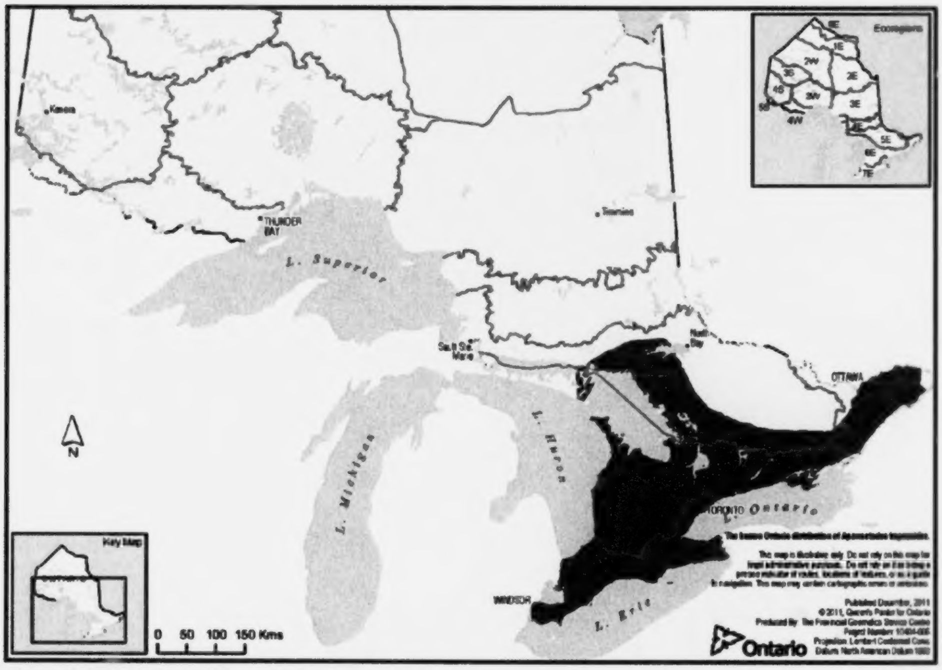

***Figure 5:** Distribution of* Aporrectodea trapezoides *(Southern worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994).*

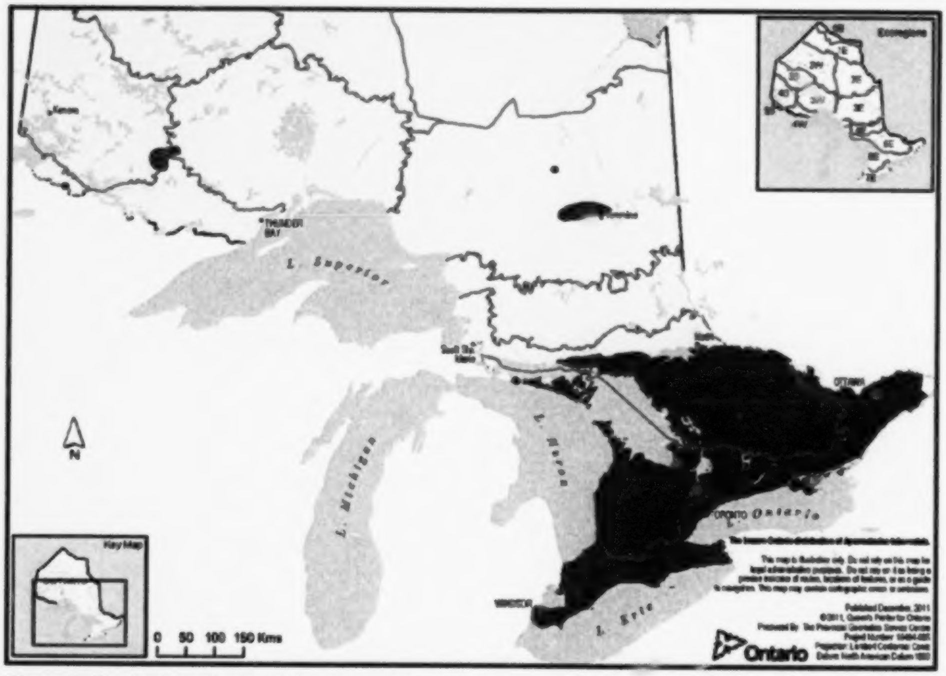

Figure 6: *Distribution of* Aporrectodea tuberculata *(Canadian worm) in Ontario (adapted from Reynolds 1977a with additional records by P.A. Gray and R. Lalonde, personal observation July 2011).*

Figure 7: *Distribution of* Aporrectodea turgida *(Pasture worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994 with additional records by P.A. Gray and R. Lalonde, personal observation July 2011).*

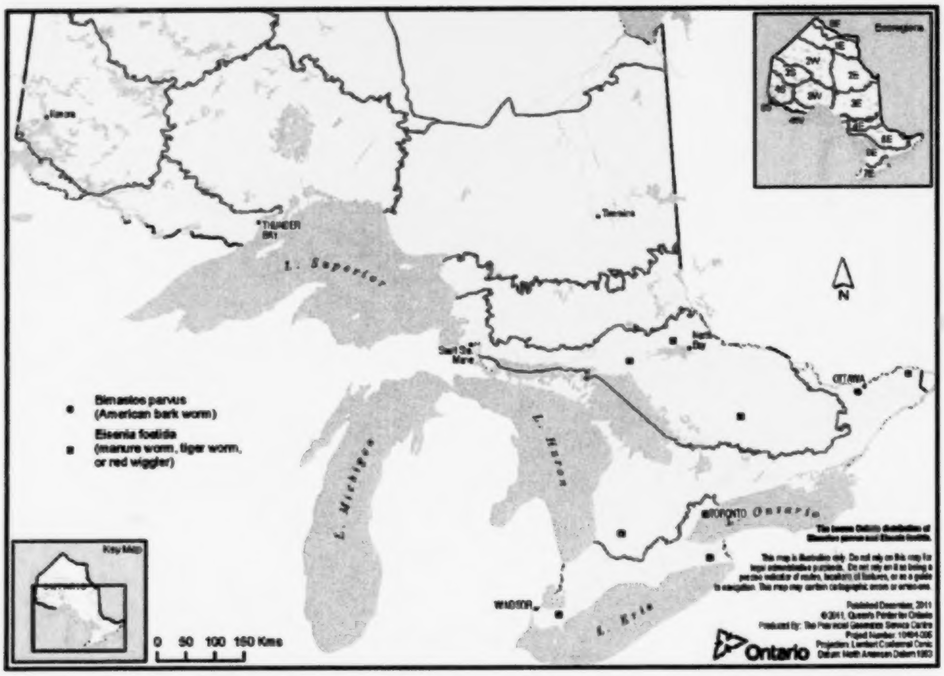

***Figure 8:** Distribution of* Bimastos parvus *(American bark worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994) and distribution of* Eisenia foetida *(Manure worm, Tiger worm, or Red wiggler) in Ontario (adapted from Reynolds 1977a with an additional record by A. Choi for the Toronto area, personal observation July 2011).*

***Figure 9:** Distribution of* Dendrobaena octaedra *(Octagonal-tail worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994).*

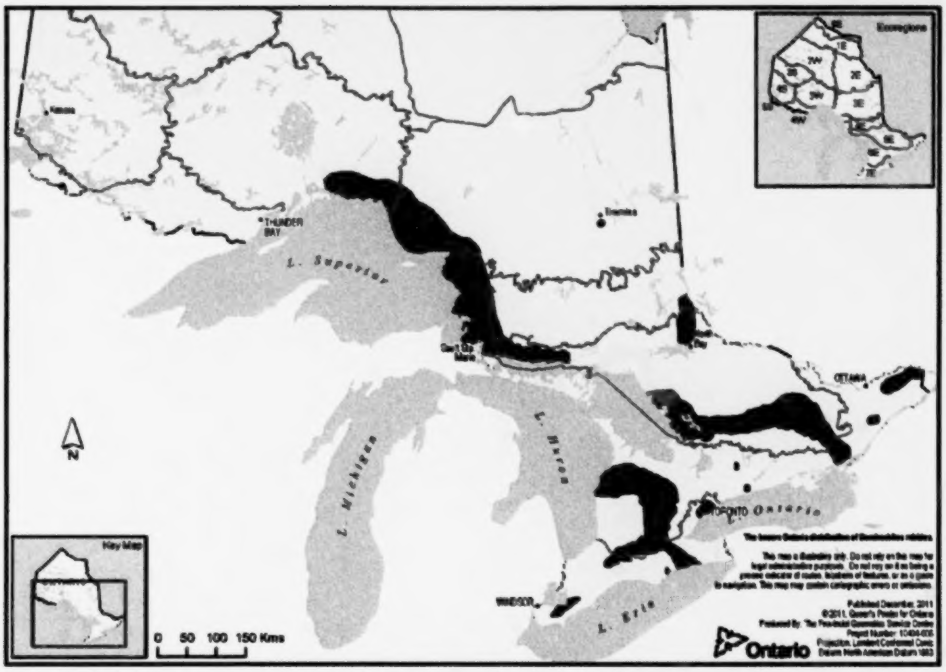

Figure 10: Distribution of Dendrodrilus rubidus *(European bark worm) in Ontario (adapted from Reynolds 1977a with additional records by P.A. Gray and R. Lalonde, personal observation July 2011).*

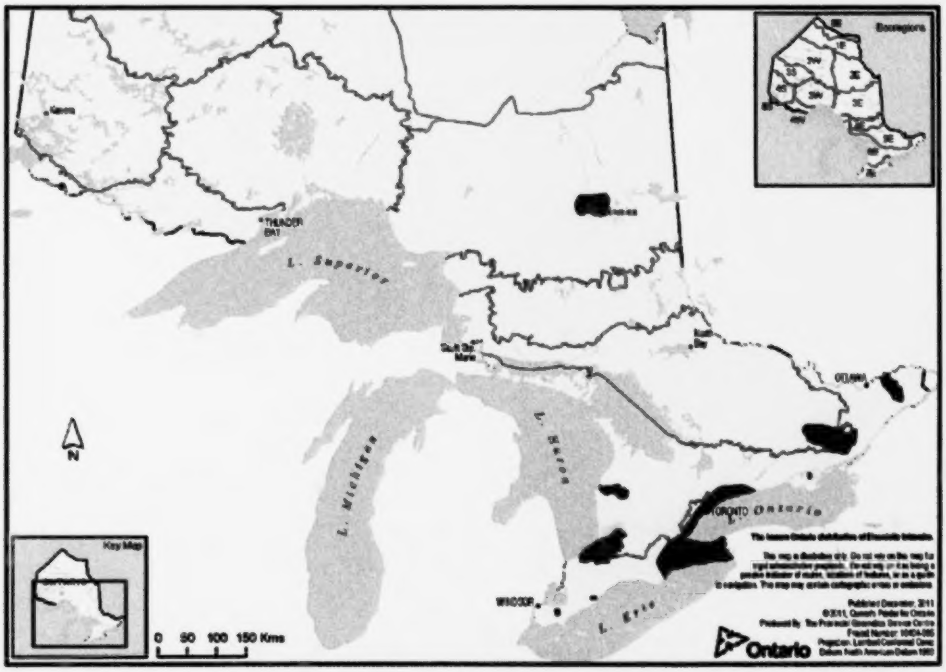

Figure 11: Distribution of Eiseniella tetraedra *(Square-tail worm) in Ontario (adapted from Reynolds 1977a).*

Figure 12: Distribution of Lumbricus castaneus *(Chestnut worm) and* Lumbricus festivus *(Quebec worm) in Ontario (adapted from Reynolds 1977a).*

Figure 13: Distribution of Lumbricus rubellus *(Red marsh worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994 with additional records by P.A. Gray and R. Lalonde, personal observation July 2011).*

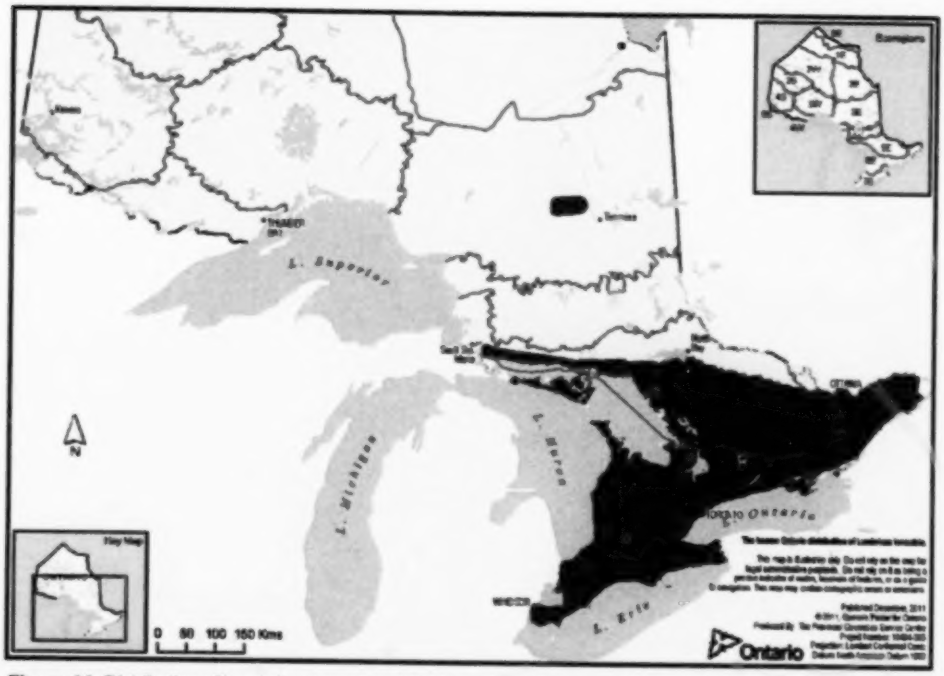

Figure 14: Distribution of Lumbricus terrestris *(Night crawler or Dew worm) in Ontario (adapted from Reynolds 1977a, Reynolds and Mayville 1994, and Tomlin and Fox 2003).*

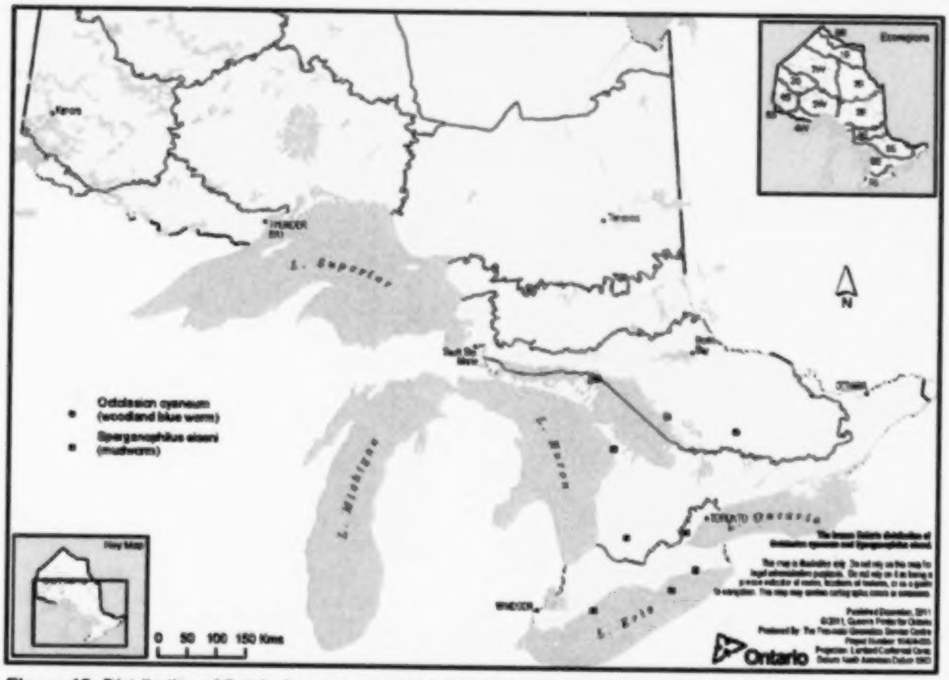

Figure 15: Distribution of Octolasion cyaneum *(Woodland blue worm) and* Sparganophilus eiseni *(American mud worm) in Ontario (adapted from Reynolds 1977a and Reynolds and Mayville 1994).*

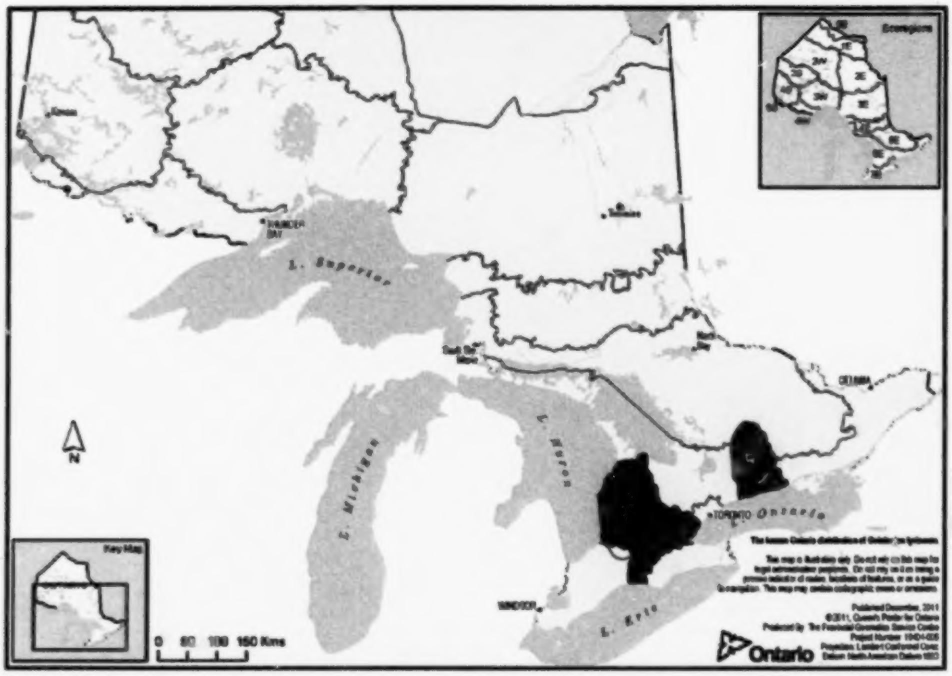

Figure 16: Distribution of Octolasion tyrtaeum *(Woodland white worm) in Ontario (adapted from Reynolds 1977a with additional records by P.A. Gray and R. Lalonde, personal observation July 2011).*

7.0 Forces and Factors Affecting Earthworm Invasion Potential

7.1 Introduction

Temperature, precipitation, and wind directly affect the distribution and abundance of organisms, because each has physiological and morphological tolerance limits (Cossins and Bowler 1987), responds to phenological cues (Root and Hughes 2005), and has niche requirements (Millennium Ecosystem Assessment 2005, Lemprière et al. 2008:18). In addition, climate indirectly affects forest ecosystem habitats and their organisms through its influence on disturbance events such as fire (Stocks et al. 1998, Flannigan et al. 2000, Li et al. 2000, Wotton et al. 2005, Colombo 2008, Stocks and Ward 2011), insects and pathogens (Fleming et al. 2002a,b; Candau and Fleming 2008), extreme events such as ice storms (Dale et al. 2001, Hopkin et al. 2003), and invasive species (Ayres and Lombardero 2000, Tiunov et al. 2006, Lemprière et al. 2008, Addison 2009, and Williamson et al. 2009).

To survive in a new habitat or persist in its current habitat, an organism must be able to complete its life cycle, and through collective physiological and behavioural responses, individuals will need to successfully meet emergent ecological challenges (often simultaneously) in the form of weather, predation, parasites, diseases, food supply, water, and shelter. Given that it is unlikely that all species will respond in the same way to climate change, species assemblages in Ontario's forested ecosystems may change in response to warmer temperatures and altered precipitation patterns. For example, studies that examine shifting climate envelopes predict that natural tree migration will be slower than climate envelope movement (Colombo 2008, McKenney et al. 2010), setting the stage for a reconfiguration of plant community composition in Ontario's

forested ecosystems. Generally, the survival, distribution, and abundance of plant species will depend on good health and access to appropriate soil types, migratory pathways, pollinator species, and asexual and sexual reproduction capabilities (Cherry 1998, Thompson et al. 1998).

In the presence of new and emerging conditions, animal species with a high rate of reproduction that can move long distances, rapidly colonize new habitats, readily use new forage or prey species, tolerate humans, and survive in a broad range of physical conditions (Rejmánek and Richardson 1996, Inkley et al. 2004) will be most successful in finding and using new niches (Gray 2005). Some earthworm species possess physiological and behavioural characteristics conducive to successful invasion of and survival in more northerly habitats, particularly if projections for warmer winter temperatures are realized and the intentional/unintentional release of worms by people continues. While many ecological factors will influence the presence of earthworm species in a warmer climate (e.g., Reynolds and Jordan 1975), commonness and geographical distribution, transportability, reproductive strategy, physiological and behavioural response to temperature, and soil pH are included in the invasion index used in this study.

7.2 Distribution and Abundance

Non-indigenous earthworm species were transported to the Great Lakes region during European settlement through the disposal of ship ballast soil and the transport of plant material (Reynolds 1977a, Lee 1985, Tomlin and Fox 2003, Tiunov et al. 2006). In recent decades, earthworm species used as fish bait have been transported and accidentally or intentionally released into soils and waters at more northerly locations. The most common and widely distributed species in Ontario are *A. chlorotica*, *A. longa*, *A. trapezoides*, *A. tuberculata*, *A. turgida*, *L. rubellus*, and *L. terrestris* (Reynolds 1977a). And given that many of them (i.e., *A. rosea*, *A. tuberculata*, *A. turgida*, *L. rubellus*, and *L. terrestris*) have reached parts of central and northern Ontario, the potential for natural or assisted range expansion in a period of rapid climate change is enhanced (Table 3).

7.3 Transportability

Given that earthworms naturally spread at a rate of up to 10 m per year or 1 km every century in suitable habitat (Dymond et al. 1997, Hale 2008), migration in response to warmer temperatures is not a significant factor, particularly in areas where suitable conditions are located in small isolated pockets of soil along stream and river banks, lake shore and riparian habitats, wetlands, and in areas dominated by exposed bedrock and shallow, highly acidic soils.

Human behaviour has been an important factor in the spread of earthworms around Ontario. For example, surface-dwelling (epigeic) and near-surface-dwelling (endogeic) species can be picked up and transported by cars, trucks, and all terrain vehicles because adults, juveniles, and cocoons of some of these species can lodge in tire treads and survive to more northerly destination points (Dymond et al. 1997, Tiunov et al. 2006, Cameron et al. 2007, Hale 2008). In addition, some species (e.g., *E. foetida*) are transported in compost and other garden materials (Tomlin and Fox 2003).

Earthworms are also transported to potential habitat as fish bait. For example, species sold to anglers in Michigan, Indiana, and Illinois included *L. terrestris*, *L. rubellus*, *D. rubidus*, and *E. foetida* (Keller et al. 2007). Although most anglers surveyed by Kellar et al. (2007) retained unused bait for future fishing trips (65%), 41% disposed unused bait on land or with trash and 12% disposed unused bait directly into a lake (note that the sum is greater than 100% because some anglers disposed their bait in multiple ways). This is perhaps why the largest earthworm populations in more northerly areas in these U.S. states occur in close proximity to lakes, streams, and boat landings. In addition, other earthworm species can be accidentally included in bait, including *D. octaedra* in Alberta (Cameron et al. 2007) and *A. chlorotica* in the southern basin of Lake Michigan (Keller et al. 2007).

The potential spread of earthworms by anglers is significant in Ontario as well. In 2005, for example, worms were the fourth most popular bait used by anglers after lures, live baitfish, and lead sinkers, jigs, and weights (OMNR 2009). It is estimated that 63.9% of all anglers who fished in Ontario during 2005 either sometimes (25.5%) or often (38.4%) used earthworms (OMNR 2009). Preliminary data for 2010 indicate similar results

***Table 3:** Selected biological and socio-economic indicators of earthworm invasiveness in Ontario.*

Species	Invasiveness Variables				
	Abundance and distribution[1]	Transportability as bait	Most northerly isotherm	pH tolerance	Parthenogenic
Allolobophora chlorotica (Green worm)	Abundant and widespread in southern Ontario	Accidental bait[2]	-10 to -15°C[1]	4.5 to 8.0[1,3]	No[1]
Aporrectodea icterica (Mottled worm)	Scarce and limited distribution	No	-5 to -10°C[1]	7.2-7.5[4,5]	No[1]
Aporrectodea longa (Black head worm)	Scarce and limited distribution	No	-5°C[1]	4.5 to 8.0[1,3]	No[1]
Aporrectodea rosea (Pink soil worm)	Abundant and widespread in southern Ontario and widespread in northern Ontario	Yes[6]	-10 to -15°C[1,7]	3.0 to 8.0[1,6]	Yes[1]
Aporrectodea trapezoides (Southern worm)	Abundant and widespread in south and east-central Ontario	Yes[1,6]	-15 to -20°C[1,7]	4.2 to 7.0[6]	Yes[1,3]
Aporrectodea tuberculata (Canadian worm)	Abundant and widespread in south and east-central Ontario Also found in northern Ontario[8]	Yes[1,6,9]	-15 to -20°C[1,7]	3.0 to 7.5[1,6]	No[1]
Aporrectodea turgida (Pasture worm)	Abundant and widespread in south and east-central Ontario Also found in northern Ontario[8]	Yes[1,6,9]	-15 to -20°C[1,7]	2.8 to 6.2[6]	No[1]
Bimastos parvus (American bark worm)	Scarce and limited distribution	No	-15°C[1]	7.5[1]	Yes[3]
Dendrobaena octaedra (Octagonal-tail worm)	Somewhat abundant in pockets, including northwestern Ontario	Accidental bait[7] Tire treads[9]	-20 to -25°C[1]	2.8 to 7.7[1,3,6]	Yes[1,3,7]
Dendrodrilus rubidus (European bark worm)	Somewhat abundant in pockets, including northern Ontario	Yes[2] Accidental bait[7] Tire treads[9]	-20 to -25°C[1]	3.4 to 6.7[3,6]	Yes[1,3]
Eisenia foetida (Manure worm)	Scarce but somewhat widespread	Yes[1,2]	-15 to -20°C[1]	6.8 to 7.6[1]	No[1]
Eiseniella tetraedra (Square-tail worm)	Relatively rare in pockets in southern and northeastern Ontario	No	-15 to -20°C[1]	6.8 to 8.5[1]	Yes[1]
Lumbricus castaneus (Chestnut worm)	Scarce and limited in distribution	No	-15°C[1]	3.2 to 8.0[1,5,7]	No[1]
Lumbricus festivus (Quebec worm)	Scarce but somewhat widespread	No	-15°C[1]	Can tolerate acidic conditions[10] 5.2 to 5.5[5]	No[1]
Lumbricus rubellus (Red marsh worm)	Common and widely distributed in southern and east-central Ontario Also found in northern Ontario[11]	Yes[1,2,5,10]	-15 to -20°C[1,7]	3.0 to 8.0[1,3,6]	No[1]
Lumbricus terrestris (Dew worm or night crawler)	Common and widely distributed in southern and east-central Ontario with a pocket in northeastern Ontario	Yes[1,6,9]	-15 to -20°C[1,7] and colder	3.0 to 8.1[1,3,6]	No[1]
Octolasion cyaneum (Woodland blue worm)	Scarce and limited in distribution	No	-15°C[1]	5.2 to 8.0[1]	Yes[1]
Octolasion tyrtaeum (Woodland white worm)	Southwestern and southcentral Ontario Also found in northeastern Ontario[11]	Potentially Yes[1,6] Accidental bait[7]	-15°C[1]	5.5 to 8.1[1,6]	Yes[1]
Sparganophilus eiseni (American mud worm)	Scarce but somewhat widespread	No[11]	Almost -20°C[1]	Likely ubiquitous	No[1]

[1]Reynolds (1977a), [2]Keller *et al.* (2007), [3]Edwards and Bohlen (1996), [4]Blakemore (1996), [5]Binns *et al.* (1999; not complete range of pH tolerance), [6]Addison (2009), [7]Tiunov *et al.* (2006), [8]specimens collected by P.A. Gray and R. Lalonde in July 2011 and identified by J.W. Reynolds, [9]Cameron *et al.* (2007), [10]Langmaid (1964), [11]No information but probably low.

(OMNR unpublished data). Because of its value as commercial bait, *L. terrestris* is a commonly transported species. In July 2011, five bait products were purchased from stores along highways 11 and 17 between North Bay and Timmins and Kapuskasing. All worms (n=108) were *L. terrestris* (P. Gray, personal observation). However, based on the literature, several other species (including *A. trapezoides*, *A. tuberculata*, *D. rubidus*, *E. foetida*, and *L. rubellus*) can be transported either as bait collected by individuals, in tire treads, or in compost (Table 3).

7.4 Reproduction

The earthworm begins life as an egg, normally protected in a case or cocoon, which hatches into a juvenile worm that matures and develops the ability to reproduce. Earthworms use different reproductive strategies, including bi-parental reproduction involving two worms and the exchange of genetic material (amphimictic) and uni-parental or self fertilization (parthenogenic).

Under the right conditions, bi-parental earthworms are semi-continuous or continuous breeders that reproduce a few times over the course of their annual lifecycle. Earthworm species that self-fertilize produce eggs by mitosis rather than meiosis (Casellato and Rodighiero 1972 in Cameron et al. 2008), and therefore the offspring are genetic copies of their parent. Under the right combination of habitat conditions, a single parthenogenic animal could establish an invasive population (Cameron et al. 2008), and multiple introductions of individuals from different locations to one site could result in a genetically diverse invasive population. While parthenogenesis tends to be an evolutionary dead end, it could result in large numbers of offspring, some of which may undergo beneficial mutations over time (Lynch 1984, Simon et al. 2002 in Cameron et al. 2008). Parthenogenic earthworm species that occur in Ontario are *D. octaedra*, *A. rosea*, *A. trapezoides*, *B. parvus*, *D. rubidus*, *E. tetraedra*, *O. cyaneum*, and *O. tyrtaeum* (Reynolds 1977a, Tiunov et al. 2006) (Table 3).

Cocoons are formed between December and February, but these are often retained in the body until hatching conditions are more favourable. Most earthworm species in the Northern Hemisphere deposit cocoons in late spring and early summer (Evans and Guild 1948). Although cocoon production and deposition decreases between August and November, it is possible that some species deposit cocoons in late fall that go dormant over winter and survive until spring.

7.5 Soil Temperature

Most earthworm species are freeze intolerant. Therefore, low temperature is one of the most important ecological factors determining their distribution (Edwards and Bohlen 1996:137). As a result of many controlling variables (e.g., surface global radiation, air temperature, soil physical properties such as albedo of the surface, water content and texture, topographical features, and ground litter), soil temperature is more moderate than air temperature, which in some circumstances may be conducive to the winter survival of earthworms (Kang et al. 2000). For example, burrowing species such as *L. terrestris* avoid freezing conditions by moving into deeper soil layers during the cold months. Other species that live on or near the surface in subarctic and cold temperate locations survive contact with frost through physiologically enabled freeze tolerance (Holmstrup 2003, Holmstrup and Overgaard 2007). Accordingly, earthworms use some combination of supercooling and burrowing, supercooling and extracellular ice-nucleating agents, and extensive dehydration to survive and persist in freezing temperatures (Block 1990; Holmstrup 1994, 2002, 2003; Holmstrup and Zachariassen 1996; Overgaard et al. 2009):

Freeze avoidance – supercooling and burrowing: The lowest body temperature that a species can endure is the point to which freezing is prevented with the accumulation of cryoprotectants such as polyols, sugars, free amino acids, or antifreeze proteins (Issartel et al. 2006). This supercooled state is called the melting point, which ranges from -0.2 to -0.4°C for many earthworm species (Holmstrup 2003). The cryoprotectants bind water molecules and reduce the probability of 'ice embryo' formation, which can destroy a cell's ability to function (Issartel et al. 2006). When this survival strategy is used, the earthworm retains body water. Given that supercooling does not work at temperatures beyond -0.5°C, freeze intolerant earthworm species such as *A. chlorotica*, *L. rubellus*, and *L. terrestris* compensate by burrowing deeper into the soil away from the frost line to survive the winter months (Holmstrup 1994).

Freeze tolerance – supercooling and ice nucleating agents: Freeze-tolerant earthworm species use supercooling at low sub-zero temperatures and protective freezing of intracellular fluids (inside the cell) at high sub-zero temperatures with extracellular ice-nucleating agents to survive in cold climates (Holmstrup and Zachariassen 1996). Protective freezing results from the presence of ice-nuclei (e.g., ice crystals, food or mineral particles, or ice nucleating agents) in the extracellular chamber of the body, which serve to draw water out of the cells. Given that water loss from the cell can cause membrane and protein denaturation (Issartel et al. 2006), freeze-tolerant animals prevent damage from dehydration through the accumulation of cryoprotectants such as glycerol (Holmstrup and Zachariassen 1996, Ramløv 2000). Only a few species, including Ontario forms of *D. rubidus* and *D. octaedra*, can tolerate internal extracellular ice formation. For example, *D. octaedra* inhabits the uppermost soil layers of coniferous forests and tundra in temperate and subarctic ecosystems (Holmstrup and Overgaard 2007, Overgaard et al. 2009), can tolerate internal ice formation, and can survive several months in a frozen state. As freezing occurs, glycogen reserves are converted to glucose, which functions as a cryoprotectant and metabolic fuel. As well, glucose preserves the structure and function of membranes and proteins during the freezing-induced dehydration of tissues (Holmstrup 2003).

Freeze tolerance – supercooling and dehydration: Even though cocoons are not freeze tolerant, many earthworm species deposit them in surficial soil layers where they dehydrate in frozen soil. Dehydration prevents cell freezing (Holmstrup 2003) and is used by organisms that have a high permeability for water, are dehydration tolerant, and can accumulate sugars and polyols that are used to protect the integrity of the cells (Holmstrup 2002). The process is somewhat similar to freeze tolerance physiology where extracellular ice formation induces dehydration of the cells. Unlike a freeze-tolerant response that conserves body water however, the strategy results in extensive dehydration of the entire organism because the water activity of ice is lower than the activity of supercooled water when at the same temperature (Holmstrup 2002). This difference in water activity results in the movement of water out of the cocoon causing dehydration. Once dehydrated, the cocoon will not freeze at high sub-zero temperatures, and therefore the chance of winter survival is significantly increased (Holmstrup 2003). The cocoons of *D. octaedra* and *D. rubidus* have lower supercooling points and survive better than *A. chlorotica* cocoons (Holmstrup 1994). Although most Lumbricid species deposit their cocoons near the soil surface when soil conditions (a function of moisture, temperature, and food supplies) are suitable, some will deposit cocoons deeper if one or more of these factors is not favourable at the soil surface.

While minimal winter soil temperatures will remain a primary determinant of the northern extent of earthworm distribution (Tiunov et al. 2006), warming winter temperatures in the 21st century may increase the amount of available habitat. The -15°C isotherm is cited by Tiunov et al. (2006) as an important limiting boundary for many invasive earthworm species that are cold intolerant. All invasive earthworm species inhabiting Ontario, except *A. icterica* and *A. longa,* have been collected from habitats within the -15°C January isotherm (Table 3, Figure 3), which currently stretches from Parry Sound on Georgian Bay in the west to Cornwall in the east (Figure 17). Most observations for some species (*A. trapezoides, A. tuberculata, E. foetida, S. eiseni, L. rubellus, L. terrestris,* and *A. turgida*) are from habitats close to or at the -20°C isotherm (Table 3, Figures 5, 6, 7, 9, 13, 14, and 15), and freeze-tolerant species such as *D. octaedra* and *D. rubidus* have been collected from locations beyond the -25°C isotherm (Figures 9 and 10) (Reynolds 1977a). Of note is the presence of a large colony of *L. terrestris* that thrives in the soil at Moose Factory (>51°N latitude) located at the southern end of James Bay (Tomlin and Fox 2003), where the average minimum January temperature is -25°C to -20°C. Over the next 90 years, the -15°C January isotherm could migrate hundreds of kilometres northward. For example, using the CGCM3-A2 scenario, the -15°C isotherm extends as far north as Thunder Bay (Figure 17).

7.6 Soil pH

Although earthworms prefer soils that are pH neutral, most species found in Ontario can tolerate acidic soils (Reynolds 1977a, Addison 2009). *A. icterica, B. parvus, E. foetida*, and *E. tetraedra* are acid intolerant species and are unlikely to thrive in northern boreal forest soils. The remaining species are moderately (i.e., *O. cyaneum, O. tyrtaeum,* and *S. eiseni*) or highly tolerant (i.e., *A. chlorotica, A. longa, A. trapezoides, A. tuberculata, A. turgida, D. octaedra, D. rubidus, L. castaneus, L. festivus, L. rubellus, and L. terrestris*), and capable of surviving in acidic soils of boreal forest ecosystems if other conditions conducive to survival and reproduction also exist. Density diminishes as soil acidity increases (Reynolds 1977a). In addition to soil pH, the palatability of leaf litter

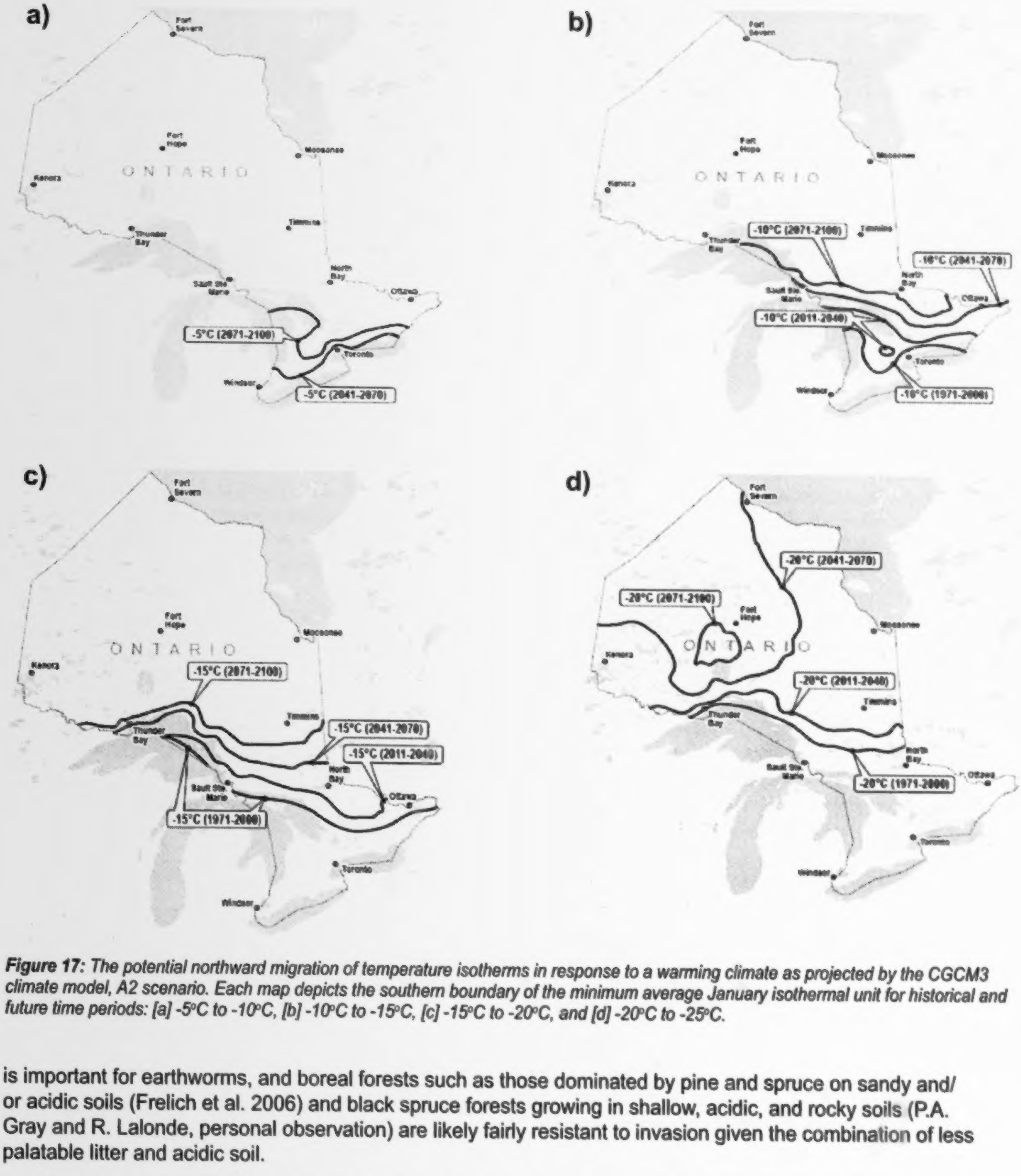

***Figure 17:** The potential northward migration of temperature isotherms in response to a warming climate as projected by the CGCM3 climate model, A2 scenario. Each map depicts the southern boundary of the minimum average January isothermal unit for historical and future time periods: [a] -5°C to -10°C, [b] -10°C to -15°C, [c] -15°C to -20°C, and [d] -20°C to -25°C.*

is important for earthworms, and boreal forests such as those dominated by pine and spruce on sandy and/or acidic soils (Frelich et al. 2006) and black spruce forests growing in shallow, acidic, and rocky soils (P.A. Gray and R. Lalonde, personal observation) are likely fairly resistant to invasion given the combination of less palatable litter and acidic soil.

Given that some boreal forest ecosystems may be replaced by different, perhaps novel, ecosystems over the next few hundred years, possibly comprising deciduous species (Gray 2005), soil conditions (e.g., pH) may become progressively more favourable for earthworms in some locations. For example, at the end of the last ice age Boreal and Great Lakes-St. Lawrence forest ecosystems expanded north as the glaciers melted, and during a warmer period from 7000 to 3000 B.P., thermal habitats were suitable for Great Lakes-St. Lawrence

forest species (a mixture of coniferous and deciduous species) as far north as Timmins before receding to a line south of Gogama (Liu 1990). It is anticipated that some Great Lakes-St. Lawrence forest ecosystem plant species will find their way north in response to warmer temperatures (McKenney et al. 2007). On the other hand, with ongoing air pollution (e.g., NOx and NH_3) that creates acid rain, acidifying effects may constrain earthworm productivity in some locations.

7.7 Potential Invasiveness of Ontario Earthworms into Northern Ecosystems

Each earthworm species was ranked and scored according to five criteria: distribution and abundance, transportability, reproduction, relationship to the minimum January isotherm, and pH tolerance (Table 4). Three epigeic species (*A. rosea, D. octaedra, and D. rubidus*), three endogeic species (*A. trapezoides, A. tuberculata, and A. turgida*), one epi-endogeic species (*L. rubellus*), and one anecic species (*L. terrestris*) ranked high as species that may be invasive as Ontario's climate warms. Therefore, some sites in Ontario may be susceptible to invasion by all three ecological groups of earthworms, which could significantly modify soil structure and chemistry and as a result affect indigenous biota.

7.8 Limitations of the Vulnerability Index

In addition to the indicators used in this preliminary assessment of vulnerability, several other biophysical variables could be used in an invasion index to assess the potential for the spread of earthworms in Ontario under a warming climate, including soil type, soil depth, soil moisture, and site-specific pH values. Although lack of data and limited funding precluded their use in this work, future studies based on updated distribution and abundance data in conjunction with knowledge about soil types and conditions will allow a more robust analysis of earthworm invasiveness.

8.0 Potential Effects on Ontario's Forested Ecosystems

8.1 Introduction

A number of earthworm-generated effects work sequentially and/or simultaneously to affect forested ecosystems, including removal of the forest floor duff layer, changes in the physical and chemical properties of the soil, direct effects on seed and seedling survival, changes in the mycorrhizal and microbial communities, and multiple species invasions (Frelich et al. 2006, Tiunov et al. 2009, Addison 2009).

8.2 Removal of the Forest Floor Duff Layer

Plant community dynamics change significantly as a result of earthworm activity, in particular the removal of the forest floor duff layer (Bohlen et al. 2004 a, b, Hale et al. 2005a). When the organic duff is consumed by earthworms and converted into mineral soil, the native understory species decline or are lost (Frelich and Holdsworth 2002). During the conversion process, the root system of many forest floor plant species growing in the upper organic horizon are disrupted (Bohlen et al. 2004c).

8.3 Changes in the Physical Properties of the Soil

Earthworms affect soil composition, structure, and function by (1) ingesting soil, breaking down organic matter, mixing soil, and depositing casts and (2) burrowing and transferring sub-surface soil to the surface and surface materials into the deeper soil layers.

Earthworm casts: As organic matter is passed through the earthworm's gut, it is broken into smaller particles and egested in casts. This process exposes a large surface area of organic matter to micro-organisms for consumption (Edwards and Bohlen 1996). Most cast deposition is created by deep burrowing species such as *L. terrestris* (Lee 1985), but surface-dwelling species found in Ontario such as *E. rosea* and *A. trapezoides* also deposit casts, especially in soils with a high bulk density (Thomson and Davies 1974). Surface casting

Table 4. *A ranking of the invasion potential of earthworms in Ontario.*

Species	Invasion Index					Invasion Potential
	Distribution and abundance	Most northerly isotherm	Tolerance of acidic soils	Reproduction[1]	Transportability as bait	
Allolobophora chlorotica (Green worm)	M	M	L	M	M	M
Aporrectodea icterica (Mottled worm)	L	L	L	M	L	L
Aporrectodea longa (Black head worm)	L	L	L	M	L	L
Aporrectodea rosea (Pink soil worm)	H	H	H	H	M	H
Aporrectodea trapezoides (Southern worm)	M	H	H	H	M	H
Aporrectodea tuberculata (Canadian worm)	H	H	H	M	M	H
Aporrectodea turgida (Pasture worm)	H	H	H	M	M	H
Bimastos parvus (American bark worm)	L	H	L	H	L	L[2]
Dendrobaena octaedra (Octagonal-tail worm)	H	H	H	H	M	H
Dendrodrilus rubidus (European bark worm)	H	H	H	H	M	H
Eisenia foetida (Manure worm, Tiger worm or Red wiggler)	M	H	L	M	M	M
Eiseniella tetraedra (Square-tail worm)	H	H	L	H	L	M
Lumbricus castaneus (Chestnut worm)	L	M	H	M	L	M
Lumbricus festivus (Quebec worm)	L	M	H	M	L	M
Lumbricus rubellus (Red marsh worm)	H	H	H	M	M	H
Lumbricus terrestris (Night crawler or Dew worm)	H	H	H	M	H[3]	H
Octolasion cyaneum (Woodland blue worm)	L	M	H	H	L	M
Octolasion tyrtaeum (Woodland white worm)	M	H	L	H	M	M
Sparganophilus eiseni (American mud worm)	L	H	H	M	L	M

[1]For the purposes of this paper, two generic categories of reproduction were selected: sexual reproduction (amphimictic) involving two worms and asexual reproduction (parthenogenic) involving one worm. Amphimictic species were assigned to the 'Medium' category and parthenogenic species to the 'High' category.

[2]*B. Parvus* is only documented from the Agriculture Canada arboretum and the conditions there may not be typical of the 'wild.' Therefore, a low invasion potential was assigned.

[3]In a sample of five bait products purchased from five different stores along Highway 11 and 17 between North Bay and Timmins and North Bay and Kapuskasing in July 2011, all of the worms (n=108) were *L. terrestris*. Therefore, *L. terrestris* was assigned a 'High' value as bait while other species mentioned in the literature and likely only used by individuals who collect their own worms were assigned a 'Medium' value.

depends on soil temperature and moisture, and is more prevalent from June to September (Evans and Guild 1947). Earthworm casts have been studied as possible locations for denitrification (Borken et al. 2000). The cast is a preferred habitat for denitrifying bacteria because more carbon is available than in the surrounding soil and oxygen concentrations are lower (Borken et al. 2000). For example, Karsten and Drake (1997) found that microbial populations were 265 times higher in the earthworm gut and cast material than in surrounding mineral soil.

Water flow and aeration: Earthworm burrowing creates tubular openings or macro-pores, which improves aeration and provides a pathway for water (Edwards and Bohlen 1996). The moisture status at the time of rainfall, rainfall intensity, soil type, and plant cover all influence the flow of water through earthworm burrows. Water infiltration through earthworm burrows is 4 to 10 times faster than in soils without earthworms (Guild 1952, Carter et al. 1982). The creation of macro-pores also increases the field capacity of some soils, thereby increasing the availability of water to plants. For example, Sharpley et al. (1979) found a threefold decrease in surface runoff from soils containing earthworm burrows, which may reduce soil erosion. Aeration can stimulate microbial activity, which increases microbial respiration rates and the subsequent release of CO_2 to the atmosphere.

Bulk density: Bulk density reflects the relationship of the mass of soil particles to volume and depends significantly on the size of the soil solids (particles or granules) and the degree of compaction. Therefore, the more space between the granules the lower the bulk density. Earthworm-free forest soils not previously ploughed tend to have lower bulk densities due to the presence of a thick litter layer and the burrowing action of native invertebrates (McLean and Parkinson 1997, Bohlen et al. 2004a). When introduced, earthworms increase the bulk density by decreasing the thickness of the forest floor. This compaction reduces the abundance of native soil-dwelling invertebrate species (McLean and Parkinson 1998a,b; Migge 2001 in Frelich et al. 2006). In European deciduous forests with mull humus soils, the actions of indigenous soil fauna mitigate the effect of earthworm activity on bulk density to some extent, but whether or not this interaction occurs in northern North American forest soils is unknown (Frelich et al. 2006).

Soil conversion: Deep burrowing species such as *L. terrestris* are responsible for the most significant breakdown of organic matter in temperate climatic zones and the conversion of forest mor soils (usually characterized by a thick organic layer on top of the soil surface) into mull soils (soils in which organic matter is thoroughly mixed with mineral soil) (Edwards and Bohlen 1996). Knollenberg et al. (1985) found that four weeks after their introduction to a floodplain in southwestern Michigan, *L. terrestris* consumed leaves equivalent to 93.8% of the annual litterfall. Langmaid (1964) reported that soils in New Brunswick, Canada were converted from mor soils to mull soils within three to four years after the arrival of earthworms. The change from mor to mull soils alters the habitat for soil microflora and the substrate for vascular plants (Frelich et al. 2006), which has significant implications for ecosystem structure and function.

8.4 Changes in the Chemical Properties of the Soil

Earthworms change the chemical composition and nutrient dynamics of soils through the ingestion and excretion of soil and litter and the mixing of soil organic matter into the mineral soil layers (Scheu and Parkinson 1994, Tomlin et al. 1995, Blair et al. 1997, Burtelow et al. 1998, Bohlen et al. 2004a,c). Important elements include carbon, phosphorus, and nitrogen:

Carbon: Soil mixing and incorporation of organic matter results in the transfer of large quantities of carbon to lower horizons from the soil surface and increases humification and decomposition rates (Wironen and Moore 2006). For example, anecic species such as *L. terrestris* transfer organic matter from the soil surface to deeper regions of the soil profile, thereby increasing carbon content deeper in the soil profile and decreasing carbon at the soil surface. In addition, earthworms stabilize organic carbon through the addition of mucous to soil aggregates and the formation of casts (Lee 1985). Overall, it is unclear whether earthworms increase or decrease the net storage of organic carbon in soil (Bohlen et al. 2004a,b; Baker et al. 2006; Wironen and Moore 2006), and perhaps it varies from ecosystem to ecosystem.

Phosphorus: Earthworm effects on soil phosphorus pools are species specific (Suárez et al. 2003). For example, forested plots invaded by deep burrowing species such as *L. terrestris* in the state of New York contained higher concentrations of total phosphorus in the top 12 cm of the soil profile. These pools are mostly phosphorus fixed in aluminium or iron hydroxides, as well as phosphorus in primary minerals such as NaOH-Pi and HCl-P. The increase in these normally unavailable phosphorus pools in plots dominated by deep burrowing species means that unweathered soil particles were transferred from deeper layers to the soil surface. Conversely, in the plots dominated by surface-dwelling earthworms such as *L. rubellus*, total phosphorus was significantly less than in plots without earthworms. *L. rubellus* could have stimulated phosphorus cycling at the soil surface, thereby decreasing the total soil phosphorus stock. These interactions could significantly affect forest vegetation because most fine roots are concentrated in the forest floor which provides 80% of their annual phosphorus requirement (Suárez et al. 2003).

Nitrogen: Earthworms use nitrogen to metabolize protein, which comprises 60 to 80% of their tissue (Edwards and Bohlen 1996). Nitrogen content ranges from 9% in *A. turgida* to 10 to 12% in most Lumbricids. An earthworm invasion could affect soil nitrogen dynamics in a variety of ways. While earthworms can increase soil inorganic nitrogen available for uptake by plants in some ecosystems, results of some studies indicate nitrogen losses (Bohlen et al. 2004a,b). Earthworms redistribute microbial biomass by moving organic matter into the mineral soil, which in turn influences carbon and nitrogen storage and respiration rates within the soil profile (Groffman et al. 2004). For example, redistributed soil carbon can stimulate microbial growth in deeper soil horizons (Li et al. 2002), which in turn increases the demand for nitrogen and reduces mineralization, nitrification, and inorganic nitrogen pools (Groffman et al. 2004). Earthworms can increase N_2O emissions (Rizhiya et al. 2007). For example, it has been projected that up to 56% of the *in-situ* N_2O emissions from some soils are caused by earthworm activity, and that annual global production of N_2O by earthworms is in the order of 3×10^8 kg (Drake and Horn 2006). One reason for this is that the earthworm gut is an ideal environment for denitrification (Karsten and Drake 1997, Horn et al. 2003, 2006) because it is anoxic and contains carbon substrates that micro-organisms use to produce N_2O (Horn et al. 2003). Denitrification is enhanced when the earthworm ingests denitrifying bacteria with organic matter (Karsten and Drake 1997; Horn et al. 2003, 2006; Rizhiya et al. 2007). When gaseous N_2O is produced, it escapes through the earthworm's permeable epidermis (Horn et al. 2003). Higher emissions result from higher earthworm density because the volume of gut available for habitation by microbial populations increases (Evers 2009).

8.5 Plant Community Structure: Direct Effect on Seed and Seedling Survival

Although earthworms have already invaded several forested ecosystems in Ontario, little is known about their effect. Some research results are available for temperate deciduous forests in North America and Europe, but little information is available for boreal forest ecosystems.

In deciduous forests where earthworms are absent, the organic forest floor continually cycles nutrients and provides a seedbed for understory plant species. Earthworms disrupt this cycle by eliminating the forest floor duff layer and uprooting herbaceous plants and tree seedlings (Hale 2004). In addition, loss of forest floor litter exposes seeds and seedlings to freezing and drought conditions as well as predators such as insects and small mammals (Cothrel et al. 1997). As earthworms affect the survival of tree seedlings, the composition of the tree layer in the resulting forest will change as well (Frelich et al. 2006). With simplification of the herbaceous plant community, invasive plant species could potentially establish and further change the composition of the tree canopy. For example, earthworms may promote the establishment of exotic plant species, such as European buckthorn *(Rhamnus cathartica)* and garlic mustard *(Alliaria officinalis)*, which are better adapted to earthworm activity than native species (Frelich et al. 2006).

It is anticipated that plant species adapted to survive in mineral soils will be favoured over those that thrive in duff seedbeds. For example, in Minnesota, earthworm activity reduced diverse communities comprising spikenard *(Aralia racemosa)*, Solomon's seal *(Polygonatum pubescens)*, bellwort *(Uvularia grandifolia)*, nodding trillium *(Trillium cernuum)*, large-flowered trillium *(Trillium grandiflorum)*, and goblin fern *(Botrychium mormo)* to less diverse communities comprising Pennsylvania sedge (*Carex pennsylvanica*) and Jack-in-the-pulpit (*Arisaema triphyllum*) (Gundale 2002, Bohlen et al. 2004c).

Given that earthworm activity increases soil bulk density and reduces and eliminates duff, which serves to absorb rain water and slowly release it into the soil, the result could be more xeric conditions favouring dry-mesic species. These drier conditions could reduce the dominance of mesic species such as sugar maple (*Acer saccharum*) and American basswood *(Tilia americana)* to dry-mesic species such as oaks and red maple *(A. rubrum)* (Curtis 1959).

8.6 Changes to the Mycorrhizal Community

A mycorrhiza is a mutualistic association between a fungus and the roots of a plant. This relationship provides the fungus with access to carbohydrates such as glucose produced during photosynthesis and in return the plant gains the use of the mycelium's large surface area to absorb water and nutrients (e.g., phosphorus and copper) from the soil (Lawrence et al. 2003). Although not well understood, a few studies suggest that earthworms can significantly affect the distribution and abundance of arbuscular mycorrhizae species relied on by many deciduous and boreal forest plant species for water and nutrient uptake.

Once earthworms re-engineer the forest soil, non-mycorrhizal plants may be favoured. Lawrence et al. (2003) report that *L. rubellus*, *O. tyrtaeum*, and *L. terrestris* reduce the colonization rate and total abundance of arbuscular mycorrhizae in sugar maple-dominated forests and speculate that this results from the physical disturbance caused by earthworm feeding and movement and the associated disruption of external mycelia and arbuscular mycorrhizae infection rates. Another reason may be the greater nutrient availability attributed to earthworm activity, which can reduce root colonization by arbuscular mycorrhizae. Lawrence et al. (2003) also found that arbuscular mycorrhizae morphology changed in the presence of earthworms. Hyphal disruption led to increased production of vesicles, a result of carbon stress that occurs when hyphae are continually being turned over by earthworm activity. Despite the fact that a few mycorrhizal plant species (e.g., *A. triphyllum* and enchanter's nightshade [*Circaea lutetiana*]) survive in soils manipulated by earthworms, most mycorrhizal plant species are negatively affected by earthworms (Hale 2004, Frelich et al. 2006). For example, *B. mormo* is a strongly mycorrhizal species, requires thick organic horizons for survival, and has been extirpated in many areas invaded by earthworms (Gundale 2002).

8.7 Effects on Microbial Populations

Soil micro-organisms affect forest soil nutrient cycling by enhancing the decomposition of organic matter, the release of nutrients, and the subsequent processes that influence the flow of these nutrients to plants (Groffman et al. 2004). In addition, the soil microbial community influences carbon and nitrogen retention, as well as fluxes of N_2O and CO_2 through respiration (Li et al. 2002). Earthworms prey on soil micro-organisms and can decrease populations in some forest floor habitats (Callaham and Hendrix 1998, Zhang et al. 2000, Groffman et al. 2004).

The effect of earthworms on microbial populations depends on the species of earthworm as well as soil conditions such as texture, moisture, and temperature. While epigeic species such as *D. octaedra* may not affect microbial activity because they forage on the forest floor and do not contribute significantly to soil mixing (McLean and Parkinson 1997), endogeic and anecic species that prey on microbial species and contribute to soil mixing are likely to have an effect.

Earthworms may also increase the amount of soil habitat available to microbial populations because they produce labile secretions and excretions that are favoured by microbial species. In addition, the earthworm gut is an ideal habitat for microbial activity and reproduction. Aeration, soil moisture, and soil structure are also improved by earthworms and can stimulate microbial activity, increasing microbial respiration rates and the subsequent release of CO_2 into the atmosphere.

8.8 Multi-species Invasions

Multiple earthworm species invasions: Key factors that contribute to the magnitude of earthworm effects on forest soils are historical land use patterns, the species composition of the invasion, the order in which they invade, and the population densities achieved. The effects on soil characteristics and associated biodiversity are greatest when earthworm species of all ecological groups (i.e., epigeic, endogeic, and anecic) invade

because they affect the physical and chemical properties of the soil in different, sometimes synergistic ways (Hale et al. 2005a). A multi-species invasion could result in the conversion of mor soil with a duff layer to mull soil comparable to soils that are ploughed. Invasional meltdown occurs when the invasion of one species facilitates the invasion of another (Tiunov et al. 2006). Most earthworm-free deciduous hardwood forests have thick organic horizons and low (mineral) soil organic matter content, which do not support robust populations of endogeic or anecic species. However, as epigeic or epi-endogeic species are introduced, they incorporate leaf litter into the mineral soil increasing the organic content and creating habitat that improves the chances of survival by deeper burrowing earthworm species (Hale et al. 2005a, Tiunov et al. 2006). Invasional meltdown can potentially influence the distribution and abundance of plant species and microbial communities as well. In locations where multi-species invasions occur, the order of invasion can be important. For example, if *L. terrestris* invades before *L. rubellus* and consumes the surface organic horizon of the forest floor, then *L. rubellus* may have little additional effect because plants would have had time to adjust to the changes. However, given that *L. rubellus* can eliminate herbs from the forest floor, the reverse order of invasion could significantly affect the diversity of the understory (Gundale 2002, Hale 2004). Some forested ecosystems in Ontario are currently undergoing multi-species invasions. For example, in white spruce-fir forest intermixed with black spruce, trembling aspen, balsam poplar, and other species (Ecosite B116Tt/Tl) near Timmins, *D. rubidus* (epi-endogeic), *L. rubellus* (epi-endogeic), and *A. rosea* (endogeic) were collected from one location and *L. rubellus* and *A. tuberculata* (endogeic) from another (P.A. Gray and R. Lalonde, personal observation).

Earthworm-white-tailed deer synergy: The white-tailed deer (*Odocoileus virginianus*) is an important species in Ontario, which has significantly expanded its northward range in response to land use change, and is projected to increase the northern limit of its range further in response to climate change (Varrin et al. 2007). White-tailed deer herbivory and earthworm soil conversion could act synergistically to alter plant community composition, structure, and function. For example, given that an earthworm invasion could reduce the amount of available browse for white-tailed deer, the increase in the deer:plant ratio could lead to a greater decline or extirpation of understory plants (Frelich et al. 2006).

9.0 Summary

It is anticipated that as a result of warming temperatures, optimal thermal habitat for earthworms in Ontario will shift northward by hundreds of kilometres. Three epigeic species (*A. rosea, D. octaedra*, and *D. rubidus*), three endogeic species (*A. trapezoides, A. tuberculata*, and *A. turgida*), one epi-endogeic species (*L. rubellus*) and one anecic species (*L. terrestris*) are potentially significant invaders that merit attention. Some sites in Ontario may be susceptible to invasion by all three ecological groups, which may significantly modify soil structure and chemistry and consequently is likely to affect indigenous biota.

10.0 Recommendations

Research

- Sponsor studies to determine the temperature tolerance of earthworms that occur in Ontario to improve projections of distribution patterns in the north and to prioritize species requiring further study.
- Refine bio-geophysical variables used to assess earthworm survivability to improve vulnerability analyses that can be used to inform adaptive management in a rapidly changing climate.
- Explore the effects of earthworm activity on the carbon, nitrogen, and phosphorus cycles, including greenhouse gas emissions, such as CO_2 and N_2O, to the atmosphere.
- Describe the effects of earthworm activity in Ontario's forests. Ecological assessments are needed that address the effects of earthworm activity on soil structure and chemistry, tree growth and productivity, understory growth and productivity, mycorrhizal communities, microbial communities, and ecosystem-level measures of productivity, such as litterfall and woody biomass production before and after invasion (Frelich et al. 2006).
- Explore the dynamics of multi-species invasions.
- Explore the relationship between earthworm activity and other invasive species, such as white-tailed deer and ticks.
- Complete research on invasion pathways to document how earthworms are spread into new, potentially viable habitats, and explore options to control the spread.

Inventory and Monitoring

- Given the potential significance of earthworm invasions into forested and possibly other ecosystems, an ongoing provincial inventory and monitoring program of the distribution, relative abundance, and effects of earthworms would help natural resource managers to better assess potential threats in support of management decisions. Existing monitoring programs should be used as part of a network.
- Update records and maps of earthworm distribution in Ontario.

Status Reports

- Much of our knowledge about earthworm distribution in Ontario is based on Reynolds (1977a) with some additional information for northern Ontario provided by Addison (2009) and Gray and Lalonde (personal observation). In addition to the 19 invasive species examined here, at least 20 new species from Asia, Africa, and South America have been introduced into North America (Hendrix and Bohlen 2002), and pose a potential threat to forested ecosystems. An updated version of Reynolds (1977a) should be compiled to provide a base for future research, policy development, and management action.

Education and Extension Programs

- Given the known and potential significance of the effects of earthworms on forested ecosystems, and given that the movement of several important species results from human activity, education and extension programs for anglers, truckers, and other members of the public are recommended.

Biological Expertise

- Given that taxonomic and ecological expertise is an important part of efforts to understand the relationship between climate change and earthworms and to develop management strategies, it is recommended that Ontario seek the expertise necessary to evaluate the threat of invasive earthworms on forested ecosystems.

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Appendix 1 – Glossary of Terms

Ammonium (NH_4^+): Derived from ammonia; inorganic form of nitrogen readily available to plants and the dominant form of nitrogen found in earthworm casts (Edwards and Bohlen 1996: 169).

Amphimictic: Bi-parental reproduction through fertilization of an ovum by a sperm (Reynolds 1977a: 18).

Anecic (also see endogeic and epigeic): Earthworms that live in permanent vertical burrows and are characterized by medium to heavy dorsal pigmentation, large size, long generation time, and a diet of surface litter (Edwards and Bohlen 1996: 306)

Arbuscular mycorrhizae: A type of mycorrhiza in which the fungus penetrates the cortical cells of the roots and forms a mutualistic relationship with vascular plants; aids in the uptake of phosphorus and other nutrients in plants (Lawrence et al. 2003).

Denitrification: The biological reduction of nitrate to nitrite to gaseous nitrogen as molecular nitrogen or oxides of nitrogen (Edwards and Bohlen 1996: 307).

Endogeic: Earthworms that burrow through the upper mineral soil and are characterized by no or light pigmentation, medium size, intermediate generation time, and a diet of mineral rich soil enriched with organic matter (Edwards and Bohlen 1996: 307).

Epigeic: Earthworms that live on the soil surface and are characterized by dark pigmentation, small to medium size, short generation time, and a diet of surface litter (Edwards and Bohlen 1996: 307).

Field capacity: Field capacity is the amount of soil moisture or water content held in soil after excess water has drained away and the rate of downward movement has materially decreased.

Glucose: The most common monosaccharide (sugar); the monomer of the polysaccharides starch, glycogen, and cellulose (Sadava et al. 2008).

HCl-P: Hydrochloric acid-phosphorus; form of phosphorus that is available to plants (Suárez et al. 2003).

Hyphae (singular, hypha): In fungi (mycorrhizae), any single filament (Sadava et al. 2008).

Meiosis (also see Mitosis): Is the cell division necessary for sexual reproduction. In animals, meiosis produces gametes like sperm and egg cells. Chromosomes in a gamete cell are a unique mixture of maternal and paternal DNA, ensuring that offspring are genetically distinct from either parent. This gives rise to genetic diversity (Chambers 1983).

Mineralization: The conversion of an element from an organic form to an inorganic form (Edwards and Bohlen 1996: 308).

Mitosis: A process of cell division that results in the formation of new cells without a change in chromosome number in these cells (Chambers 1983).

Mor (also see Mull): A type of forest soil in which there is little mixing of surface organic matter with mineral soil, with a sharp transition between the surface organic horizon and underlying mineral horizon (Edwards and Bohlen 1996: 308).

Mull: A type of forest soil in which the surface horizon consists of organic matter and mineral soil thoroughly mixed together, with a gradual transition to the underlying horizon (Edwards and Bohlen 1996: 308).

Mycelium: The mycelium (plural mycelia) is the vegetative part of a fungus that consists of a mass of branching, thread-like hyphae.

Nitrate (NO_3^-): Inorganic form of nitrogen readily available to plants; formed through nitrification.

NaOH-Pi: Sodium hydroxide-orthophosphate; labile form of phosphorus (Suárez et al. 2003).

Parthenogenesis: Reproduction in which the ovum develops without being fertilized by spermatozoa; only involves one parent (Edwards and Bohlen 1996: 308).

pH: A measure of acidity, or the activity of hydrogen ions. It is the logarithm of the reciprocal of hydrogen ion concentration (Kimmins 2004).

Soil horizons: The various layers exposed in a soil.

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